

PROGRESS REPORT
NO. QSR-14C0172-OCEAN ACOUSTICS-033115

Contract No. N00014-14-C-0172
Office of Naval Research

Task Reporting:
Deep Water Ocean Acoustics

For the Period:
January 1 to March 31, 2015

Prepared:
April 15, 2015

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Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 15 APR 2015		2. REPORT TYPE		3. DATES COVERED 00-00-2015 to 00-00-2015	
4. TITLE AND SUBTITLE Deep Water Ocean Acoustics				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Ocean Acoustica Services and Instrumentation System,Inc., 5 Militia Dr., suite 104,,Lexington,,MA,02421				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 15	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

Cost Summary

OASIS, INC.

JOB STATUS REPORT

3/31/2015

1172 DEEP WATER ACOUSTICS

N00014-114-C-0172

POP: 9/27/13-3/6/16

CONTRACT VALUE

	Cost	Fee	Total
Contract Value	\$368,935	\$27,048	\$395,983
Funding Value:	\$215,404	\$15,791	\$231,195
Remaining to Fund:	\$153,531	\$11,257	\$164,788

CUMULATIVE SPENDING WITH COMMITMENTS

	DIRECT	OH	MH	TOTL COST	FEE	TOTAL
ACTUAL						
OASIS	\$77,884	\$57,155	\$1,747.00	\$136,786	\$10,259	\$147,045
COMMITTED						
	\$0	\$0	\$0	\$0	\$0	\$0
	\$77,884	\$57,155	\$1,747	\$136,786	\$10,259	\$147,045
TOTAL REMAINING TO SPEND:						\$84,150

Technical Summary

- Refer to the attached Quarterly Report for Deep Water Ocean Acoustics.

Deep Water Ocean Acoustics

Quarterly Report

ONR STTR N12A-016

Dr. Kevin Heaney
OASIS Inc.

Period of Performance: January 1, 2015 – March 31, 2015

I. Introduction

The goal of this research is to increase our understanding of the impact of the ocean and seafloor environmental variability on deep-water (long-range) ocean acoustic propagation and to develop methodologies for including this in acoustic models. Experimental analysis is combined with model development to isolate specific physics improve our understanding. During the past few years the physics effects studied have been three-dimensional propagation on global scales, deep water ambient noise, under-ice scattering, bathymetric diffraction and the application of the ocean acoustic Parabolic Equation to infrasound.

II. Peregrine Development

In order to benchmark Peregrine against both RAM and NSPE work was conducted to set up and run specific range-dependent benchmark problems. During this period of performance Dr. Heaney successfully completed the comparison of Peregrine to Ram for range-independent and range-dependent cases. This was done at 250 Hz, 1kHz and 3.5 kHz. In order to get the models to agree the following things had to be done:

- 1.) Adjust the peregrine water depth so that the seafloor depth matched that of Ram (this involved 1 grid shortening of the water column),
- 2.) Explicitly defined the geo-acoustics so that both models had the same sponge
- 3.) Output the complete computational grid, and smoothed both results after the fact, rather than using the code discrete output,
- 4.) Turned off Thorp attenuation.

A single example of this comparison is shown in Figure 1 below, where for a range-dependent environment (flat, upslope, flat) RAM is compared with Peregrine.

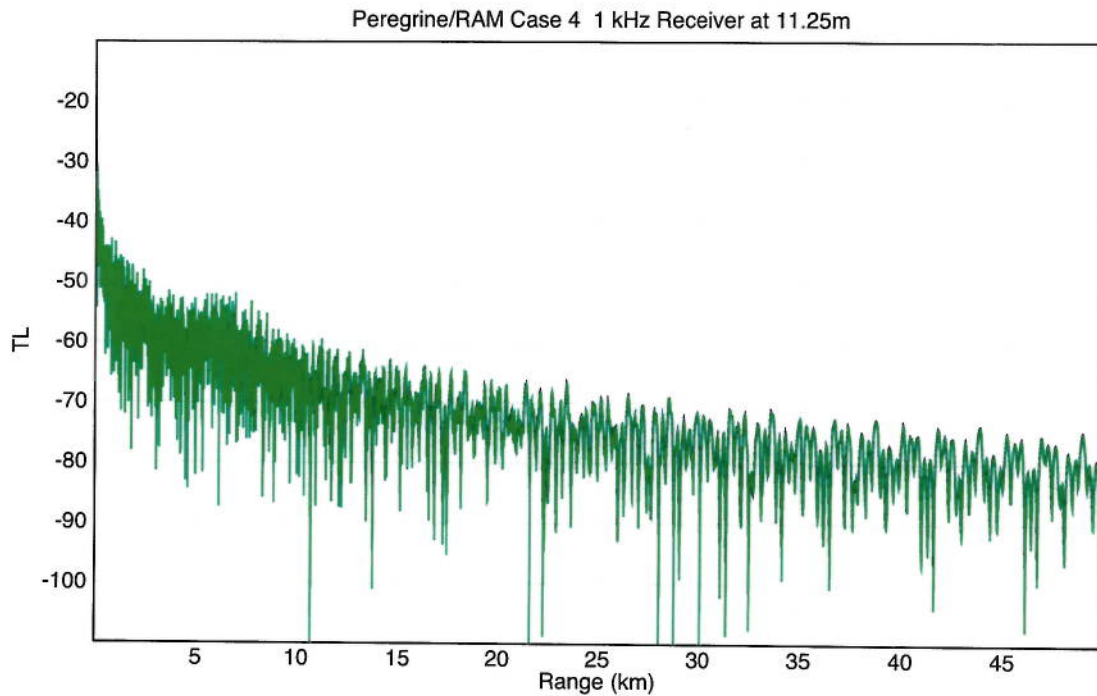


Figure 1. Range-dependent (upslope) comparison of Peregrine and RAM for 1 kHz.

The kernel of Peregrine is a small subroutine named Seahawk. Seahawk.c, as a subroutine, can be directly integrated into NSPE (Navy Standard Parabolic Equation), permitting testing of the Seahawk/Peregrine algorithm without worrying about environmental interpretation. This procedure was performed and documented. The NSPE and NSPE_Seahawk comparison for the NSPE test case 5 is shown below. Agreement is excellent.

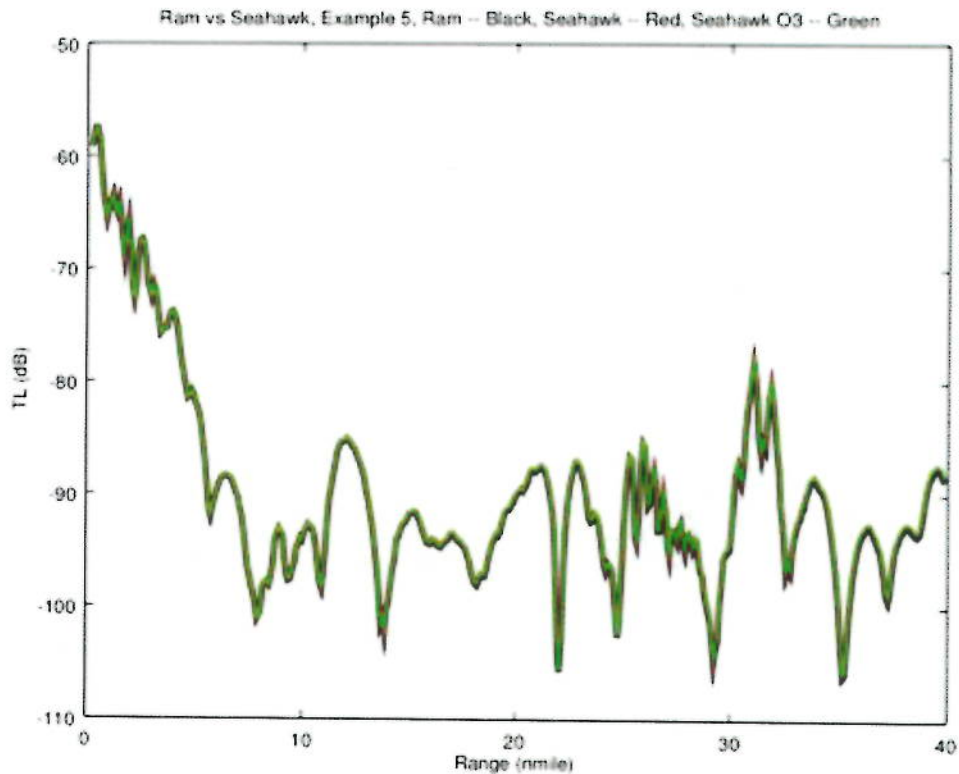


Figure 2. Range-dependent (Downslope) comparison of NSPE and NSPE w/ RAM for the NSPE Test Case 5.

Modeling active and passive ASW performance in the changing Arctic requires an approach that incorporates changes in environmental characteristics (ice roughness, thickness and ocean sound speed) as well as efficient range-dependent computation capability. To this end, OASIS has developed an equivalent fluid Parabolic Equation model (Peregrine) that propagates through an explicit realization of a range-dependent ice sheet abiding by the keel depth statistics of first year ice. The model, which approximates shear loss with volume loss in the ice (through a high attenuation coefficient), matches the broadband shot data in (Diachok, 1976) taken under first year ice in the Beaufort.

The high-angle PE model will accurately capture forward scattering effects due to ice roughness on very short spatial scales. The Peregrine PE model is a fluid-fluid model¹ and is not expected it to capture the shear loss or the re-conversion of shear energy back into compressional energy in the water column. To approximate the loss due to shear conversion, an effective ice parameter model will be used that attenuates energy via volume attenuation. The parameter space for the ice acoustic parameters will be compressional speed ($c_p=1450-1630$ m/s), attenuation ($a=0-10.0$ dB/l). In order to successfully attenuate enough sound to match the data a 1m additional thickness for low frequencies (under 200 Hz) was required. This inversion led to a compressional speed of 1560 m/s and an attenuation of $a=0-10.0$ dB/l).

Peregrine has been submitted to OAML for inclusion as the Navy Standard Parabolic Equation. This approach accurately models the forward scattering of the field underneath the rough sea-ice surface, a requirement for examining sonar performance issues associated with coherence, signal time spread and multipath stability. In Figure ## below, the model transmission loss results for a 600 Hz transmission are shown for climatology (World Ocean Atlas) and for a measured profile taken from the ITP program. The impact of the ice is seen in the high attenuation and the breakup of the structure of deep propagating high-angle rays. The presence of the duct at 150m is demonstrated to have a significant impact on the propagation.

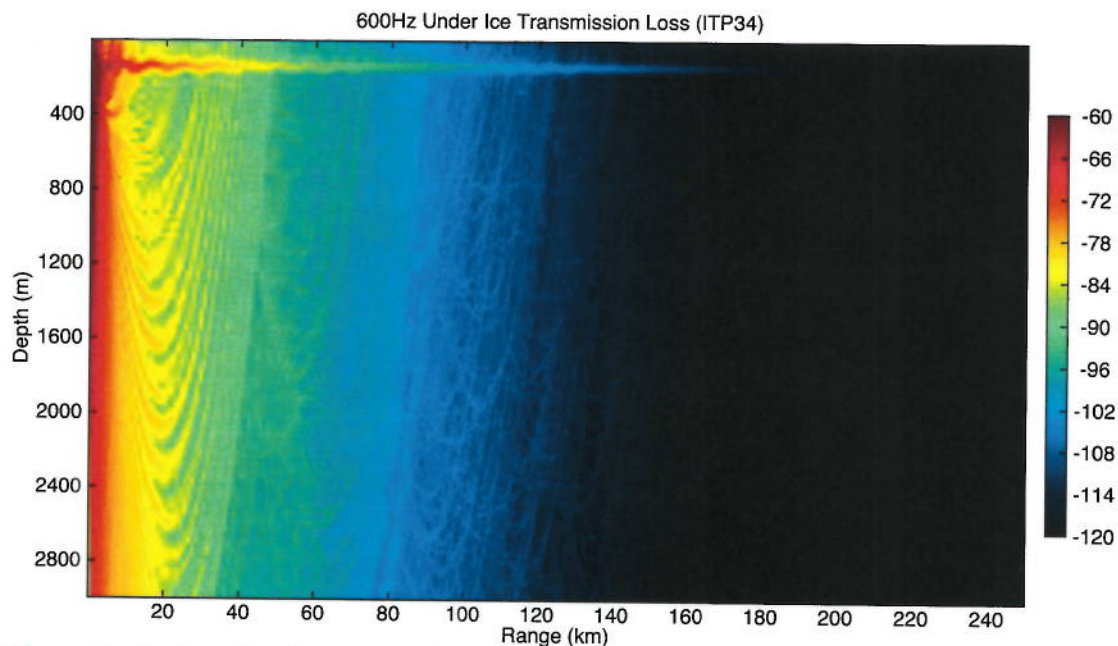


Figure 3. Updated under-ice profile with a 600Hz source in the observed as part of the Ice Tethered Profile program.

An active ASW simulation is conducted with a 1-second 600Hz broadband signal, including surface reverberation (-20 dB ice scattering strength, 90 degree bearing sector) as well as explicit computation of the broadband echo (+10 dB Target Strength). Vertical aperture to reduce the reverberation (and ambient noise) has not been included in this computation. For these parameters, detection in the climatological ocean (left panel) is challenging due to reverberation and signal loss, but when there is a duct present (right panel) the slight reduction in reverberation and the increase in target echo permits detection out to ambient noise limited ranges on the order of 100 km or more.

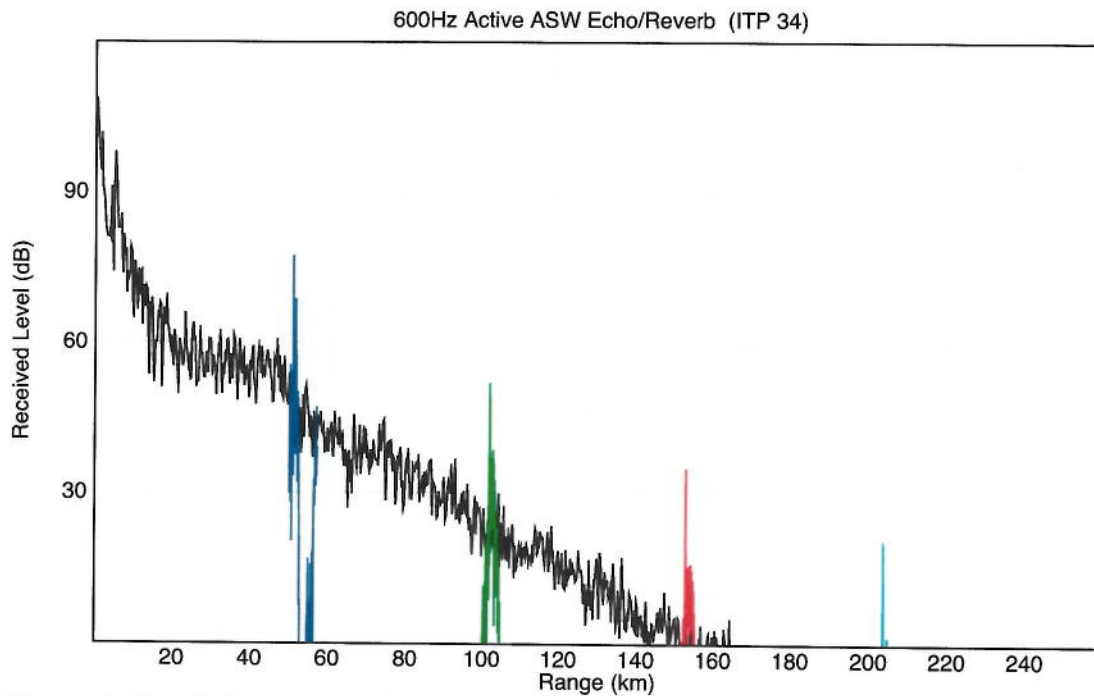


Figure 4. Parabolic equation based monostatic under-ice reverberation (black) and broadband target echo (colors) for a source/target in the duct.

Peregrine efficiently handles 3-dimensional propagation in ocean. Investigations are underway to see if the model can compute the 3D infrasound field for a large low-frequency source (explosion) in the atmosphere. Atmospheric propagation is inherently 3-dimensional due to the slow speed of sound and the fact that wind speeds approach 10-30% of the sound speed and therefore propagation depends upon direction relative to the wind. Dr. Heaney ran 2D and 3D cases of infrasound coverage maps based upon the simple approximation of using the dot-product between the wind vector and the propagation direction as the effective sound speed. 0.25, 0.5 and 1 Hz runs were done to 3000 km from central Europe.

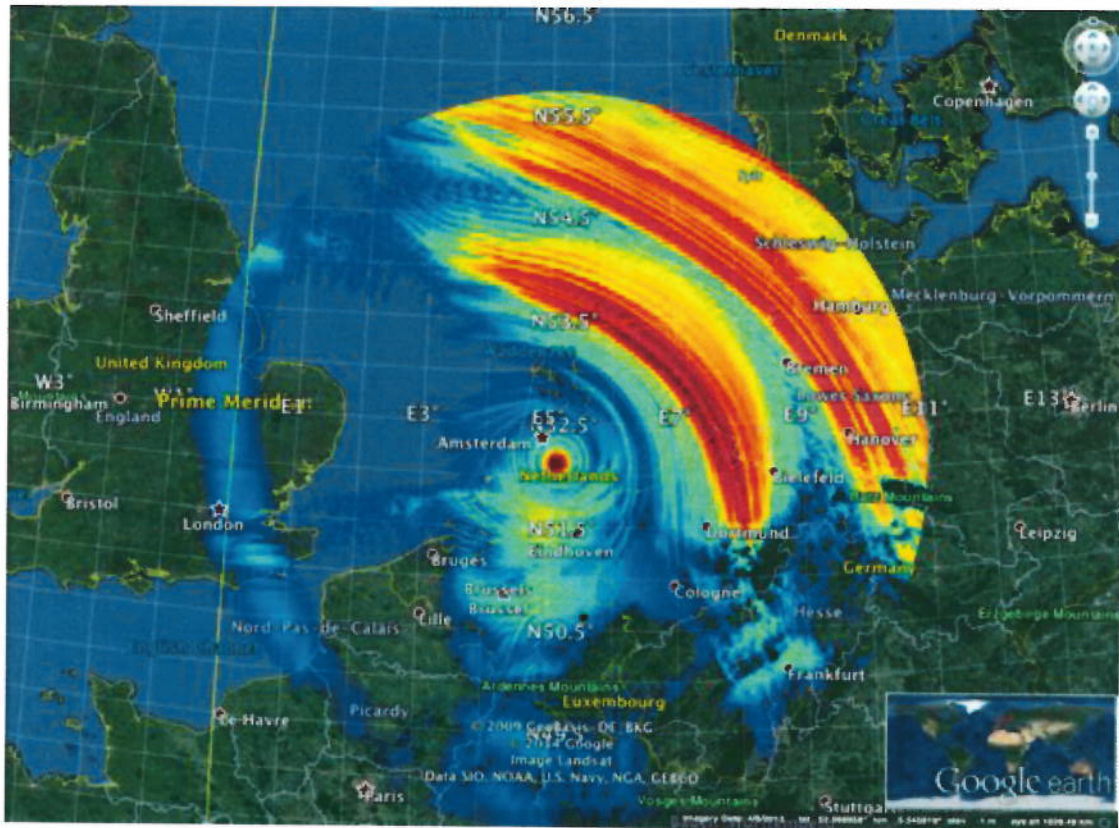


Figure 5. Infrasound 3-dimensional propagation using Peregrine at 0.5 Hz with a global wind-field from the ECMWF forecast.

III. Philippine Sea Vertical Line Array Noise Analysis and Modeling

During this quarter, Dr. Heaney processed the VLA data from PhilSea09 below the reciprocal depth. Observed the J-15 transmitted tones. The reflection coefficient was mapped by taking the difference of the up and the down going waves, using the method of Harrison and Siderius². The objective of this work is to build a high-fidelity model for estimating the structure and levels of deep water ambient noise.

IV. Mesoscale Three-Dimensional Effects on Propagation

The ECCO2 model is an eddy-resolving reconstruction of the ocean temperature/salinity fields generated on every 3 days. The Sea Surface Temperature of the ECCO2 model is shown in figure 6. Two years of the model were downloaded and a notional earthquake at Kerguelen ridge source with a detection at the CTBTO H10 Ascension Island array was used for acoustic propagation. Note that this sound travels through the Agulhas

retroflexion, a region postulated by Munk³ to induce significant angle deviation (although he found it incapable of explaining the Perth Bermuda experimental results.)

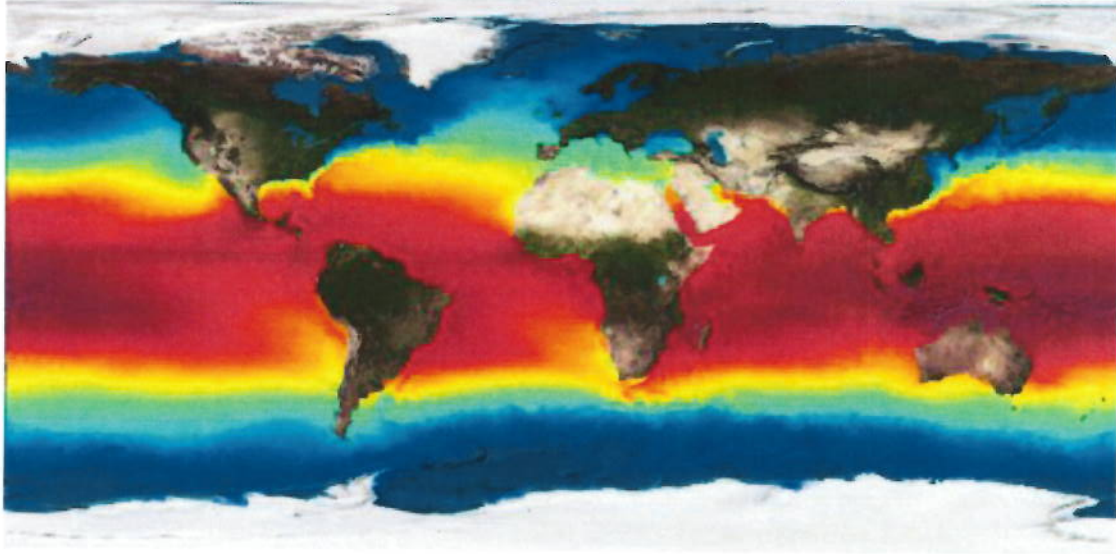


Figure 6. Sea Surface Temperature (SST) from the ECCO2 eddy-resolving model for January 3, 1992.

The procedure was to run the 3D PE model with a 10000 km window around the geodesic. Running Peregrine this way, with acoustic sponges at the edges, reduces the computation time and memory requirements for global propagation runs. The complex pressure field was stored on a 3 km x 3 km planar array of receivers, which was then beamformed to determine the arrival angle of the narrowband signal. During the period of performance Dr. Heaney completed runs from Kerguelen to Ascension through two years of the ECCO2 model. This was done with the 3D Peregrine at 2, 4, 8 and 16 Hz frequencies. Sixteen Hz was done every month and all the other frequencies were done every 3 days (1 Ecco2 output field). The arrival angle was computed and shown to have over 1.5° spread in the arrival angle with seasonal dependence. The World Ocean Atlas model was also used as a benchmark. The results for 2, 4, 8, 16 Hz are shown in Figure 7.

These results show that mesoscale refraction (there is no impact of bathymetry for this path except at 2 Hz) leads to a variability in the arrival angle of ~ 1.5°. The arrival angle is clearly modulated seasonally, although there is high-frequency (3-15 day) variability. There is some seasonal coherence across frequency. The impact of a 1.5° back azimuth bearing error on source localization at ranges of 9000 km is illustrated in Figure 8, where the acoustic field is shown, as well as the source/receiver geodesic (red) and the estimated location using the measured back azimuth (blue).

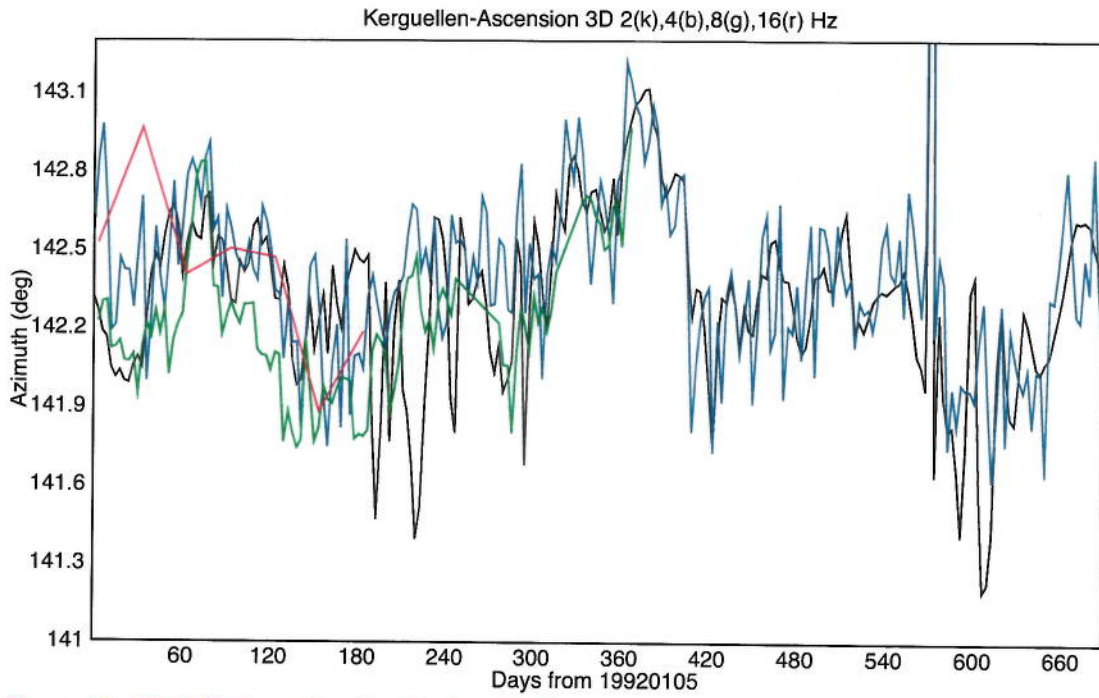


Figure 7. Modelled received arrival angle for a source near Kerguelen (South Indian Ocean) and a planar receiver array at the HA10S (Ascension) island location.

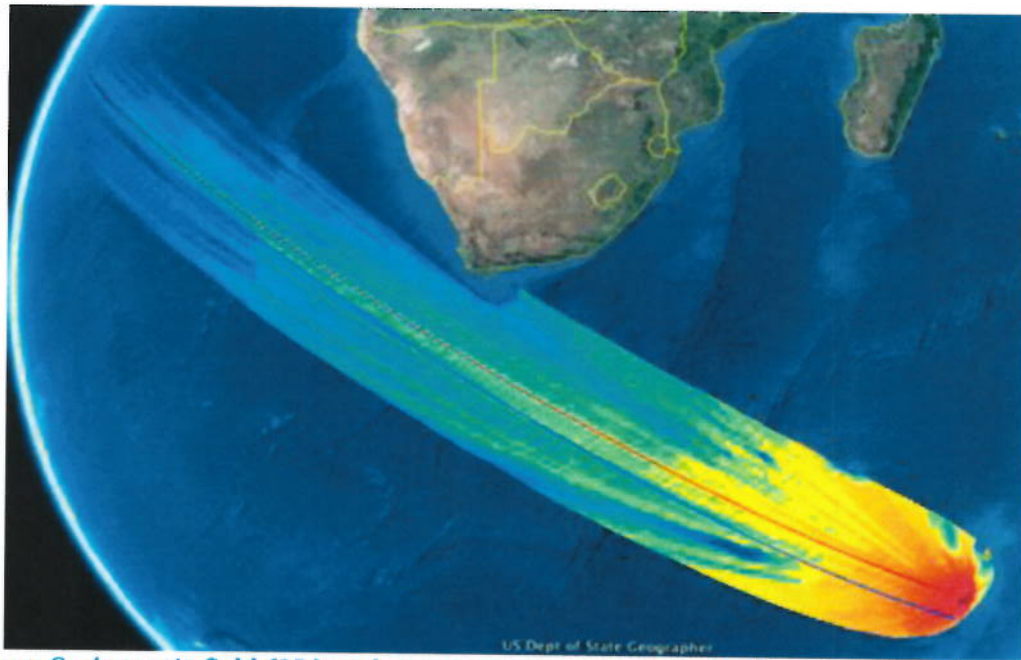


Figure 8. Acoustic field (3D) and source-receiver geodesic (red) and estimated position using the measured back azimuth.

V. CTBTO Data Analysis and Global Propagation Modeling

Dr. Heaney worked with Dr. Laslo Evers and Pieter Smets (KNMI) to obtain 4 data sets from the CTBTO. We found a magnitude 5.5 earthquake on the East Pacific Rise, that could possibly be heard on Diego Garcia both from the Atlantic path and the Pacific. When we downloaded this data, we did not find any evidence of the earthquake. Propagation distances are on the order of 18000 km. Processed the Ascension and Diego Garcia CTBTO data set for May 12, 2009 looking for seismic receptions. I found receptions on Ascension North, Ascension South, and Diego Garcia North/South. Oddly, for the airgun transmit data, only the Diego Garcia South seismic signals had a 10s pulse repetition interval (PRI), meaning all of the arrivals on the other stations are from different airguns. Magnus Christensen of PGS has provided shot locations and times for an airgun survey off the coast of Brazil. It is hoped that we can use these signals to evaluate decades of ocean warming via ocean acoustic tomography. The airgun data provided only corresponds to airguns received at Diego Garcia in the Indian Ocean and not those received on Ascension.

CTBTO Observations of Airgun Surveys JD132 2009

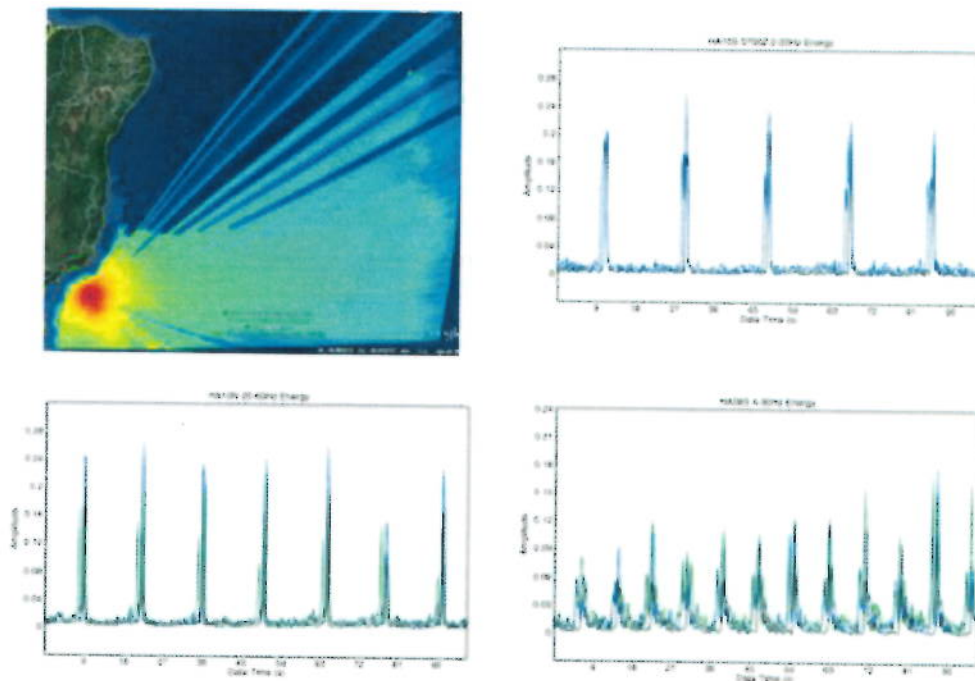


Figure 9. 3D PE model run from airgun location to Ascension island. Processed data for airgun receptions at Ascension North (HA10N), South (HA10S) and Diego Garcia (HA08S). Each of these show high SNR receptions of airguns – albeit different guns because of the different Pulse Repetition Interval.

OASIS generated global scale high-resolution images showing 3D acoustic propagation for Perth-Bermuda, Heard Island and each CTBTO station (Ascension, Wake Island, Juan Fernandez, Crozet, Cape Leeuwin, and Diego Garcia). These figures will be projected on a 15 ft 3D globe at the Navy Science and Technology Fair at the Convention Center in Washington DC on February 4/5th. These results were provided to Dr. Mario Zampolli at the CTBTO as well and will form the foundation of my talk at the Science and Technology meeting hosted by the CTBTO in Vienna in June.

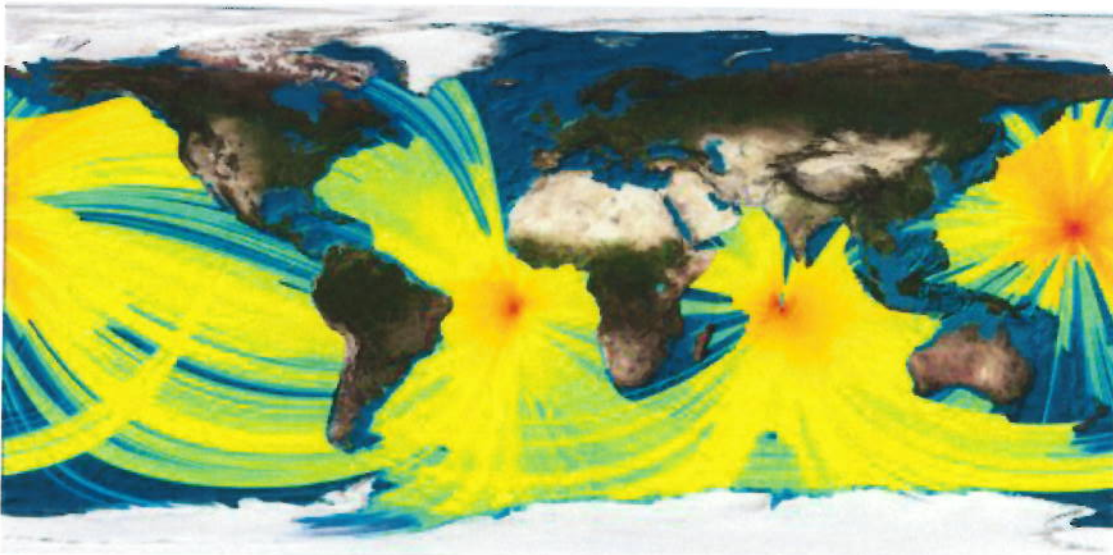


Figure 10. 3D PE model run showing the coverage of the partial CTBTO system.

Dr. Heaney delivered the global scale runs to Reggie Beach at ONR for presentation on the OmniGlobe (a 2 m 3D projection of the earth) at the Navy Technology Summit. Ray asked me to do some deep water Philippine Sea ambient noise modeling. Peregrine was run for the PhilSea09 deep VLA (DVLA) array out to all regions of the basin, including upslope towards Taiwan and the Philippines.

VI. Planetary Acoustics

The Peregrine model handles source/receiver geometry and environmental inputs in a geoid based reference frame, allowing figures like 10 to be generated directly. To apply Peregrine to Europa, three features within Peregrine needed to be changed. First, the radius of the planet, used to generate all of the geodesics and longitude/latitude references for sources and receivers, was changed to 1541 km. The second is the placement of an ice sheet as an absorptive layer. We use an angle-dependent absorption, which is best deduced by experiment, but for the purpose of this paper was set at 0.5 dB per bounce at normal incidence. The ocean depth is set to 100 km, and the sound speed profile (shown below in Figure 9C) is taken directly from Leighton et. al.⁴. In their paper, they point out that the added weight of the 20 km ice cover doesn't only add to the increased pressure, it also acts as a gravitational attractor and must be included. The effect of the smaller planetary radius relative to ocean depth is also considered, and the pressure vs. depth is therefore computed as an integral of the depth-dependent gravitational force. The sound

speed profile is range-independent; since there is little expectation there will be significant mesoscale phenomenon given the lack of solar heating of the sea. The final environmental modification for this paper was the inclusion of a sinusoidal sea floor with a 10 km amplitude, 50 km correlation distance. As artificial as this sounds, we have no prior information on topography of the Europa seafloor and simply want to investigate the impact of large-scale roughness (mountains, etc) on propagation in a 100km deep ocean.

Deep Source Propagation on Europa

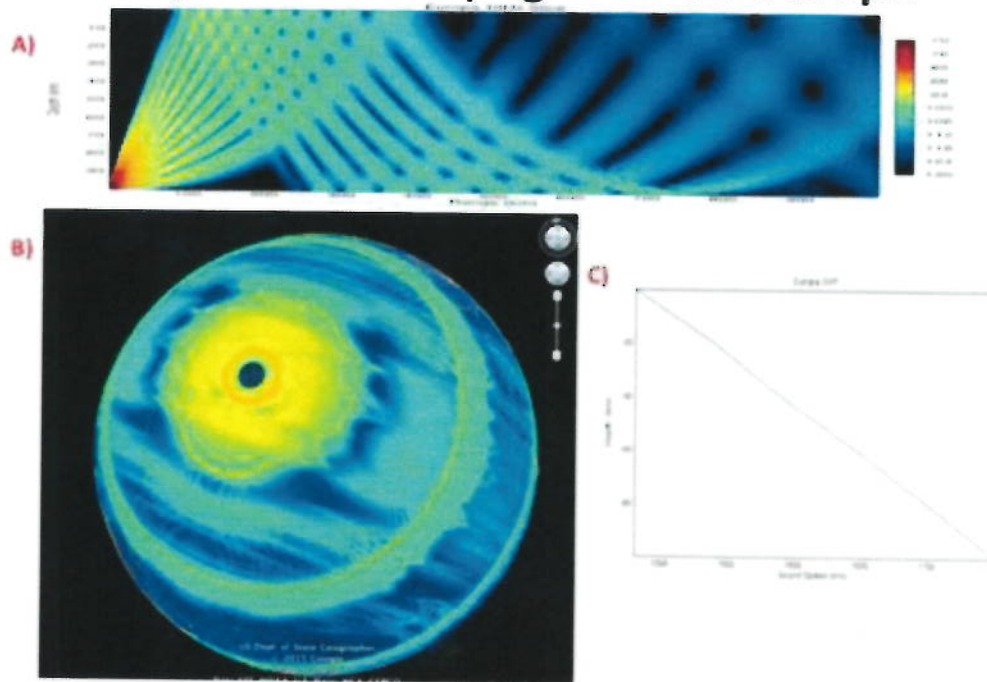


Figure 11 Low Frequency (10 Hz) Deep Source Acoustic Propagation on Europa. A) A 1000 km range/depth slice for a source near the seafloor (99 km) below the ice layer. B) Planetary 2-dimensional propagation for a deep source to a receiver near the sea-ice boundary. C) Sound speed profile in the Europa Ocean..

VII. Publications and Peer Interactions

Dr. Heaney wrote a paper and submitted it to the International Conference of Sound and Vibration, on planetary acoustic propagation on a small ice covered moon. H submitted a paper as a co-author with Prof. Jen Miksis-Olds (ARL-PSU) on the variability of detection range for marine mammals due to variability in the measured ambient noise for 3 CTBTO stations. The paper's title is "ESOMM-2014: The Impact of Ocean Sound Dynamics on Estimates of Signal Detection Range". Dr. Heaney worked with Dr. Michael Ainsle and Ozkhan Sertlik to finish touches on a JASA paper comparing analytic

mode computational results with the parabolic equation for range-dependent Weston Memorial Workshop problems.

Met with Dr. Michael Ainsle to discuss propagation in the North Sea, and the implications of 3-Dimensional propagation on Navy Sonar Performance Prediction. Met with Prof. Walter Munk, Prof. Bill Kuperman, Dr. Tyler Helble, Dr. Steve Lynch and Dr. Michael Hedlin to discuss global propagation, marine mammal localization performance using our model and infrasound modeling. Attended the ONR Technology Summit and had discussions with Dr. Bob Headrick, Dr. Scott Harper, Lee Frietag, Dr. Gerald D'Spain and Dr. Ray Soukup.

- 1 Michael Collins, "A split-step Pade solution for the parabolic equation method," *Journal of the Acoustical Society of America* **93** (4), 1736-1742 (1993).
- 2 Chris H. Harrison and Martin Siderius, "Effective Parameters for Matched Field Geoacoustic Inversion in Range-Dependent Environments," *IEEE Journal of Ocean Engineering* **28** (3), 432-445 (2003).
- 3 Walter Munk, W. C. O'Reilly, and J. L. Reid, "Australia-Bermuda Sound Transmission Experiment (1960) Revisited," *Journal of Physical Oceanography* **18** (12), 1876-1898 (1988).
- 4 Timothy G. Leighton, D. C. Finfer, and P. R. White, 2007.